

## SIMULATION OF ULTRASOUND PROPAGATION ACROSS INTERFACES WITH IMPERFECT CONTACT

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### INTRODUCTION

In elastic materials the propagation of ultrasonic waves is governed by the Christoffel's equation, which relates the displacement vector as a function of time and position to the stiffness tensor at that point. If the material is inhomogeneous, an analytical solution of the partial differential equation becomes exceedingly difficult or impossible, especially in the presence of non-trivial boundary or initial conditions. Finite Difference Equations (FDE) provide a very convenient tool for the solution of partial differential equations (PDE's) in media, in which the physical properties are homogeneous or vary continuously, such as Epstein Layers. Otherwise the use of FDE's may be justified only as an approximation. In fact, for the conversion of derivatives into finite differences, a "smoothing" of the variables across the interfaces is required and, if the discontinuity is sharp, severe errors or ambiguities may result [1,2].

In order to overcome this difficulty, a Sharp Interface Model (SIM) has been proposed [3]. By assuming perfect contact, i.e. imposing the continuity of displacements and stresses at the interface between different media, iteration equations can be obtained for any kind of interface and heterogeneities. SIM is based on the Local Interaction Simulation Approach (LISA), which has been developed in refs. [4,2,5] for the treatment in 1-D, 2-D and 3-D media, respectively. LISA has been designed to take full advantage of massively parallel computing, such as provided by the Connection Machine. The most important feature of parallel processing, with respect to applications to materials studies, is the mutual

independence of the processors. By putting them into a one-to-one correspondence with the “cells” of the specimen (properly discretized) one can assume that each cell may have different physical properties, since the corresponding processors are mutually independent. All the material properties are assigned as initial data to each processor via a front-end computer. Thus (almost) arbitrarily complex media can be treated without increasing the computer time. As a result one can visualize [6] the wave propagation at any time and place after the interrogating beam with a known displacement vector has been launched into the medium at a given time (generally  $t=0$ ) and position ( $x=0$ ). Knowledge of the displacement vector at a given point, in turn, reflects the elastic properties of the material through which the wave has propagated. Such a simulation can indeed be very helpful in the analysis of complex NDE data.

In this paper we extend the LISA technique to the case of specimens having interfaces with imperfect contact between different materials. In fact the mechanical integrity of interfaces is of paramount importance in determining the reliability of many structural components. As a consequence, a nondestructive characterization of interfaces, e.g. by ultrasonic techniques, is required for the prediction of the strength and life expectancy of a structure (together, of course, with an analysis of the relation between interface flaws and mechanical properties of the specimen).

Several theoretical models as well as experimental results dealing with the propagation of ultrasound across imperfect interfaces may be found in the literature: see e.g. ref. 7, which is a special issue of the Journal of Nondestructive Evaluation entirely devoted to the topic. For brevity we do not review it here, but restrict ourselves to a short description in the next Section of a spring model, which can be used to derive, heuristically, the iteration equations for the ultrasonic pulse propagation in the case of perfect contact and to extend the treatment to imperfect contact interfaces. Finally in Section 3, we present and discuss a few examples of numerical simulations of pulse propagation through interfaces with delaminations or other kinds of interface flaws.

## THE MODEL

It is possible to derive heuristically the iteration equations, needed for the simulation of the ultrasonic wave propagation in both homogeneous and heterogeneous media, by means of a simple spring model. In the model, the specimen is first discretized with grid points representing tiny homogeneous regions as “cells” of materials. Across the grid points a network of strong springs is assumed, to ensure an elastic behavior inside each material component and, in the case of perfect contact interfaces, a perfect contact among different components. Figure 1 gives a pictorial representation of the spring model, in the case of a homogeneous material, by depicting the interaction of a generic grid point P with its nearest neighbors through a set of springs, labeled as  $F_1$  to  $F_8$ .

If the grid point P happens to be an interface point between different materials at the right and left of the vertical through P, then the two vertical springs ( $F_6$  and  $F_8$ ) are each split into two separate springs, according to the physical properties of the corresponding material. More generally, if P is a cross point at the intersection of two orthogonal interfaces separating four different materials, then all four horizontal and vertical springs are split each into two springs as shown in Fig. 2.

It is thus possible to obtain the iteration equations for the displacements of a pulse propagating into a discretized medium (which can be arbitrarily complex, since each grid point may well be a cross point). The details of the derivation of the iteration equations are omitted here for brevity. As a further step, one can also model the interface contact by means of additional springs. The node point P is split into four “subnodes”,  $F_1$ ,  $F_2$ ,  $F_3$  and  $F_4$ , connected through internal springs. Several different kinds of interface flaws may then be modeled by assuming that the internal springs are weakened or broken. Some of them will be studied in the following Section.

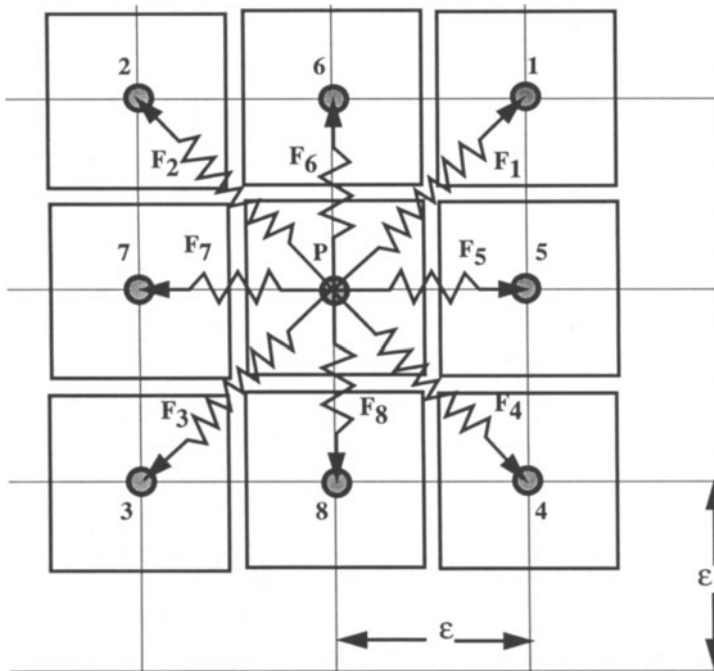


Figure 1. Spring Model for a generic grid point P in the case of a homogeneous material.

## RESULTS AND DISCUSSION

We consider a plexiglass/aluminum bilayer with a vertical interface between the two materials. Figures 3, 4 and 5 represent (i.e plots at a fixed time) of the whole displacement field. A gaussian or plane source pulse is assumed to have been injected from the left side ( $x=0$ ). The time of the snapshot is in all cases somewhat after the crossing by the pulse of the

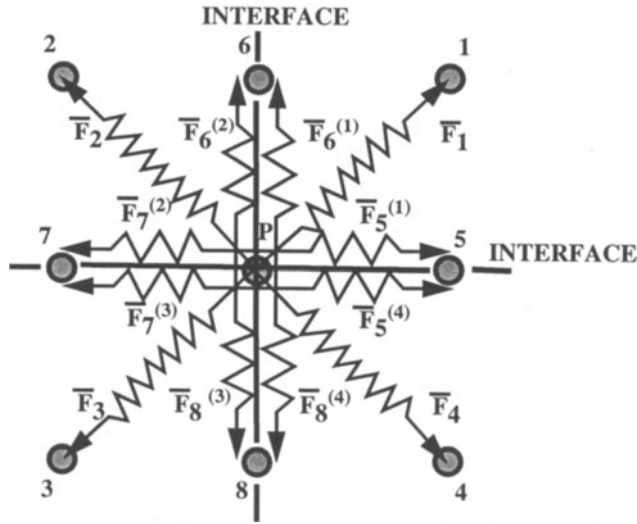


Figure 2. Representation of the forces involved in the Spring Model for heterogeneous materials.

interface. Thus both reflected and transmitted pulses can be seen in each plot. The interface is located at  $x = 40$  arbitrary units (a.u.). The *Lame'* constants (in units of  $10^{12}$  dynes/cm<sup>2</sup>) and mass densities (in gm / cm<sup>3</sup>) of the materials are  $\lambda_1 = 4.4$ ,  $\mu_1 = 2.09$ ,  $\rho_1 = 1.2$  for plexiglass and  $\lambda_2 = 56.0$ ,  $\mu_2 = 26.0$ ,  $\rho_2 = 2.7$  for aluminum.

Figure 3 represents the propagation of a longitudinal gaussian pulse in the two left plots and of a longitudinal plane pulse in the two right plots. In the top plots there is perfect contact, while a long (40 a.u.) interface delamination is assumed to be present in the bottom plots. Thus Fig. 3a (perfect contact, gaussian pulse) displays a transmitted pulse with a faster longitudinal front and a trailing mode-converted shear front. To the left of the interface we can observe a complex pattern due to the interference between the tail of the incoming pulse and the reflected component (both longitudinal and mode-converted shear). Fig. 3b (perfect contact, plane pulse) shows the two (transmitted and reflected) pulses with varying amplitudes (depending on the elastic constants of the two materials) and no mode conversion. Fig. 3c (imperfect contact, gaussian pulse) is similar to Fig. 3a except for the "shadow" of the delamination, eating away much of the transmitted pulse. As a consequence the reflected pulse is much stronger. Finally, Fig. 3d (imperfect contact, plane pulse) also shows the shadow of the delamination. In addition, diffraction patterns develop at both ends of it.

In Fig. 4 we compare the effect of a delamination (left plots) and of a thin gap (right plots) on the propagation of a longitudinal plane pulse. The gap in the left plots consists of a column of empty cells: 7 in the top left plot (Fig. 4a) and 61 in the bottom left plot (Fig. 4c). The difference between left and right plots is small but noticeable in the upper plots. It is negligible in the lower plots, since, being the delamination very long (61 a.u.), its width in

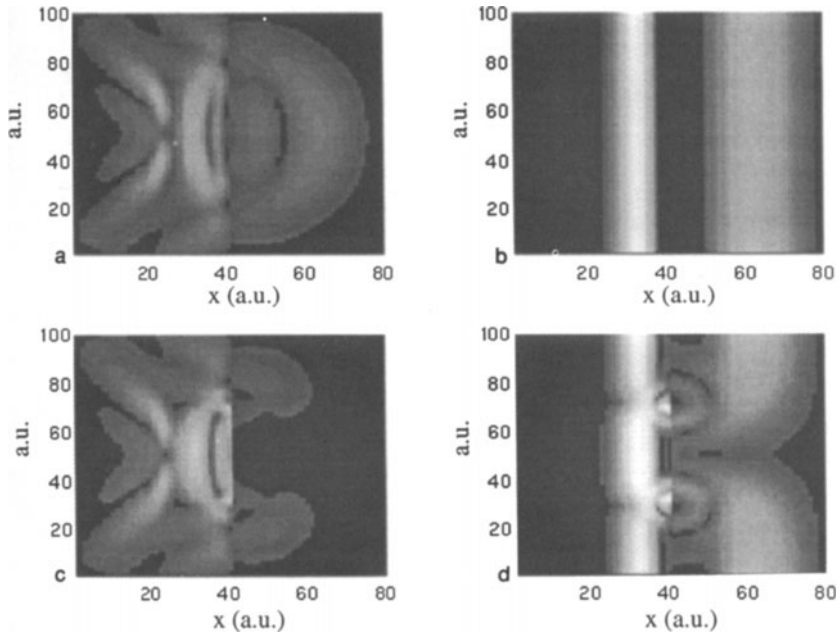


Figure 3. Snapshots of longitudinal pulses in a Plexiglass/Aluminum bilayer: a) perfect contact, gaussian pulse; b) perfect contact interface, plane pulse; c) 40 a.u. long interface delamination, gaussian pulse; d) 40 a.u. long interface delamination, plane pulse.

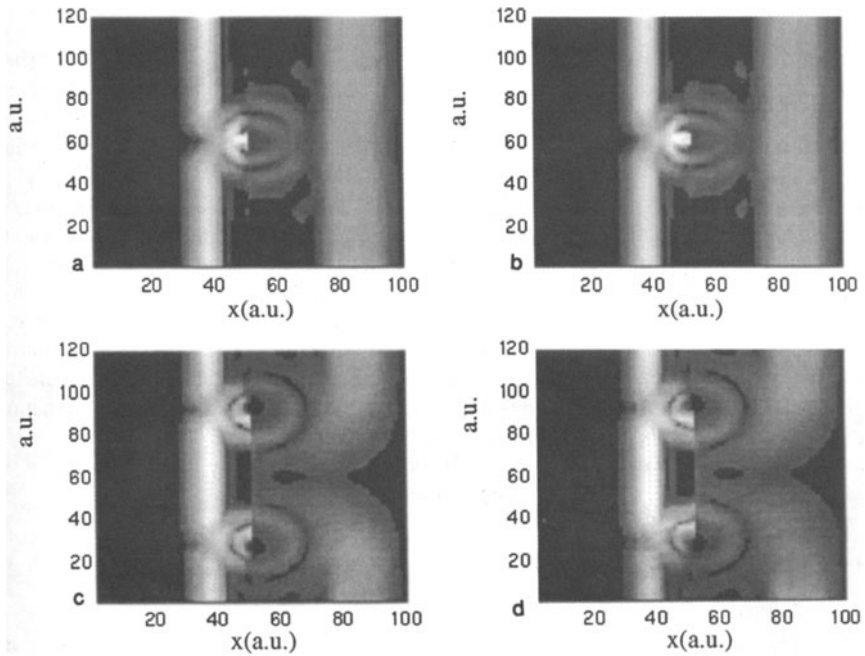


Figure 4. Plane longitudinal pulses propagating in Plexiglass/Aluminum bilayer interface with: (a) a 7 a.u. delamination; (b) a 7 a.u. gap; (c) a 61 a.u. delamination; (d) a 61 a.u. gap.

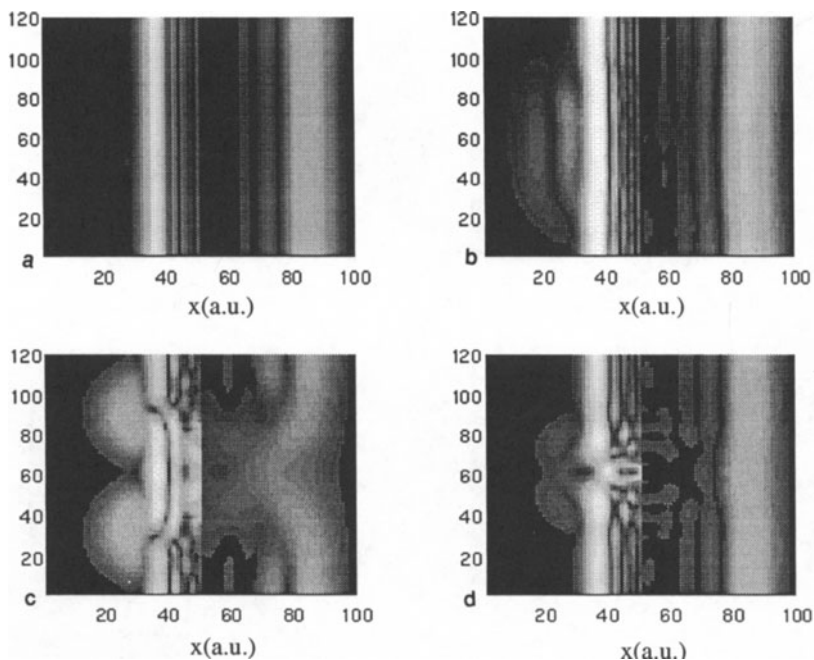


Figure 5. Snapshots of shear pulses in a Plexiglass / Aluminum bilayer: (a) Perfect bond; (b) 61 interface cells with internal spring broken between upper and lower subnodes; (c) 61 a.u. interface delamination; and (d) 7 a.u. interface delamination.

the case of the gap (1 a.u.) becomes irrelevant. In Fig. 5 we consider the propagation of shear plane pulses. Fig. 5a shows the reflected and transmitted pulses in the case of perfect contact. In Fig. 5b the internal springs between upper and lower subnodes are broken for a column of 61 cells. Thus discontinuities are created in the wave front. This results in mode conversion, following a mechanism similar to the one observed at the edges of a rectangular pulse [1]. The resulting longitudinal pulse, travelling much faster than the reflected shear pulse, may be seen to the left of it in front of the delamination. In Fig. 5c the internal springs between left and right subnodes are broken for a column of 61 cells. This imposes a barrier, whose effect is again a shadow in the transmitted pulse and a stronger reflected pulse. Also diffraction patterns develop at the edge of the delamination, as in Figs. 3d and 4c. They are, however, projected forwards (i.e. to the left) since faster longitudinal pulses are created, while in the previous cases slower shear components were left trailing behind. Finally, Fig. 5d refers to a situation similar to the one considered in Fig. 5c, except for the much shorter delamination (only 7 a.u.). Thus there is not enough space for the creation of a real shadow in the transmitted wave and the diffraction pattern is further complicated by the interference between the effects on the two edges of the delamination.

## SUMMARY

In this paper, we have described a two dimensional spring model for bonded structures and shown results of simulation of propagation of longitudinal and shear pulses (gaussian as well as plane pulses) through a bonded bilayer of plexiglass and aluminum. The simulated scattered wave shows the effect of a perfect bond, delaminations as well as a gap (poor bond)

on the wave propagation in the chosen medium. These results could be useful in the analysis of complex ultrasonic NDE data for evaluation of bonded structures.

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